9. Define at least six different categories or types of structural loads.
10. What happened in the picture below? Analyze the situation from shipbuilder’s point-of-view.

Lecture 8 : Powering, Machinery, and Equipment

Ships are self-powered systems of systems. Their machinery produces energy needed for propulsion, manoeuvring, accommodation, anchoring, mooring and if applicable cargo handling equipment. Onboard machinery must have a high power to weight ratio to ensure efficient ship propulsion. To ensure profitable shipping operations propulsion / power generation systems and their fuels tanks should also accommodate for as low space as practically possible. Within this context it is envisaged that energy efficiency and environmental friendliness should always counterbalance sound safety standards. Study of a ship's operational profile is fundamental to the above (Figure 8.1). It helps determine the ship's power demand under real environmental and operational conditions i.e. from port and in transit to docking and over a period of time of casual operations. This information may be used to estimate propulsive efficiency and compliance against IMO emission regulations.

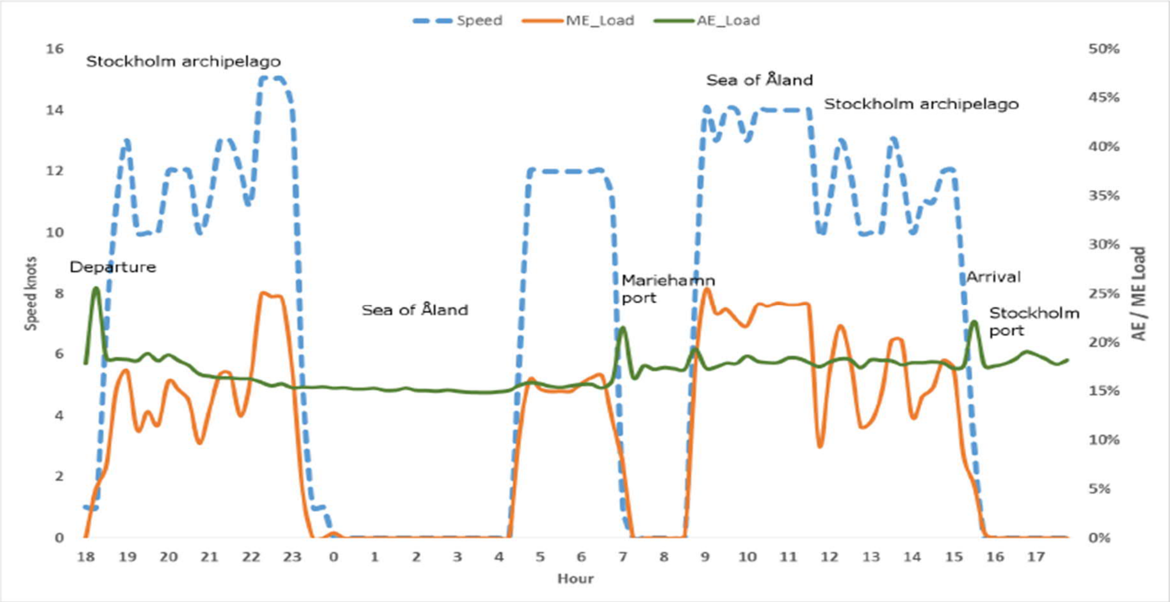


Figure 8.1 Example of an operating profile of a ship (Image credit : Baldi et. al., 2018)

This section provides a brief introduction on basic machinery (engines), fuels, propulsors (propellers, azimuths, pods) and equipment (mooring, anchoring, evacuation) found on ships. Since our focus is on principles that may directly influence concept ship design discussion on the complete range of machinery, equipment and component items (e.g. electrical generators, piping, sewage, ballast refrigeration and air conditioning systems, fire fighting /protection, deck machinery and cargo handling equipment, etc.) are not presented. The keen reader could find concise information on ship knowedge items in Van Dokkum (2020) and Taylor (1996).

1. A note on available energy sources

The energy used for marine propulsion can be derived from various sources depending on a ship's main machinery systems. Traditional **fuel oil products** are petroleum products classified as : (a) **MDO** (Marine diesel oil) - a blend of heavy gas oil that may contain very small amounts of black refinery feed stocks, with low viscosity up to 12 centistokes so heating for use in internal combustion engines is not necessary ; (b) **IFO** (Intermediate fuel oil) is a blend of gasoil and heavy fuel oil, with less gas oil than marine diesel oil; (c) **HFO** (Heavy fuel oil) - pure or nearly pure residual oil, with very high viscosity. These products are the most polluting in nature.

Taking into account the large share contribution of shipping to the in the worldwide transport market (80% of world trade by volume, 3% of global greenhouse gas emissions and contributing to air pollution close to coastal areas and ports), the gradual adoption of alternative fuels by shipping is expected to would have a significant positive immediate environmental impact. The obvious alternatives are

liquified natural / petroleum gas products (LNG / LPG), biofuels, hydrogen fuel cells, methanol, ammonia, renewable energy technologies (e.g. wind, solar; see Figure 8.2**), batteries, nuclear.** There are various factors that influence design and operations and should be considered while choosing the energy source of a vessel. In brief key factors are **energy density, availability, price**. Figure 8.3 outlines comparison of some of those based on a study by DNVGL(2019).Today, LNG is the most promising alternative fuel in the sense that it is socially acceptable, resources are available and engine technology is well under development. Notwithstanding exploration of new resources, improved international port / bunkering infrastructure and novel LNG based engines will have to develop further for this energy source to prevail.

(a)Image Credit: https://www.maritime-executive.com (b) Image credit : https://safety4sea.com

Figure 8.2 Wind assisted propulsion solutions

Energy source		Fossil (without CCS)					Bio	Renewable(3)		
Fuel		HFO + scrubber	Low sulphur fuels	LNG	Methanol	LPG	HVO (Advanced biodiesel)	Ammonia	Hydrogen	Fully-electric
High priority parameters										
• Energy density		🟢	🟢	🟩	🟩	🟩	🟢	🟡	🟠	🔴
• Technological maturity		🟩	🟩	🟩	🟡	🟡	🟢	🟠	🟠	🟡
• Local emissions		🟠	🟠	🟩	🟩	🟩	🟠	🟡	🟢	🟢
• GHG emissions		🔴	🔴	🟠 (2)	🟠	🟠	🟩	🟢	🟢	🟢
• Energy cost		🟢	🟩	🟢	🟡	🟩	🟠	🔴	🔴	🔴🟡🟢 (4)
• Capital cost	Converter	🟩	🟢	🟩	🟩	🟩	🟢	🟩	🔴	🟢
	Storage	🟢	🟢	🟡	🟩	🟩	🟢	🟩	🔴	🔴
• Bunkering availability		🟢	🟢	🟩	🟡	🟡	🔴	🟠	🔴	🟠
Commercial readiness (1)		🟢	🟢	🟢	🟩	🟩	🟡	🟠	🔴	🔴🟡🟢 (5)
Other key parameters										
• Flammability		🟢	🟢	🟢	🟩	🟢	🟢	🟠	🔴	🟢
• Toxicity		🟢	🟢	🟢	🟡	🟢	🟢	🔴	🟢	🟢
• Regulations and guidelines		🟢	🟢	🟢	🟩	🟡	🟢	🟡	🔴	🟩
• Global production capacity and locations		🟢	🟢	🟢	🟡	🟩	🟠	🟡	🟡	🔴

(1) Taking into account maturity and availability of technology and fuel.
(2) GHG benefits for LNG, methanol and LPG will increase proportionally with the fraction of corresponding bio- or synthetic energy carrier used as a drop-in fuel.
(3) Results for ammonia, hydrogen and fully-electric shown only from renewable energy sources since this represents long term solutions with potential for decarbonizing shipping. Production from fossil energy sources without CCS (mainly the case today) will have a significant adverse effect on the results.
(4) Large regional variations.
(5) Needs to be evaluated case-by-case. Not applicable for deep-sea shipping.

Figure 8.3 DNV GL's interpretation of results and evaluation of status of viability for different alternative fuels (internally rated), within selected assessment parameters (i.e. potential barriers). 2020 compliant conventional fuels have also been included for reference and for these the given colour is based on a simplified assessment by DNV GL(2019).

2. Basic engine types

The **diesel engine** is a type of internal combustion engine which ignites the fuel by injecting it into hot, high-pressure air in a combustion chamber. Diesel cycle engines are characterised by the direct injection of fuel into the combustion chamber. The fuel is ignited by the high temperatures arising from the large mechanical compression of the air prior to fuel injection. The power delivered from an engine depends on the torque it can develop at a given rotational speed (angular velocity, ω) and the rotational speed itself:

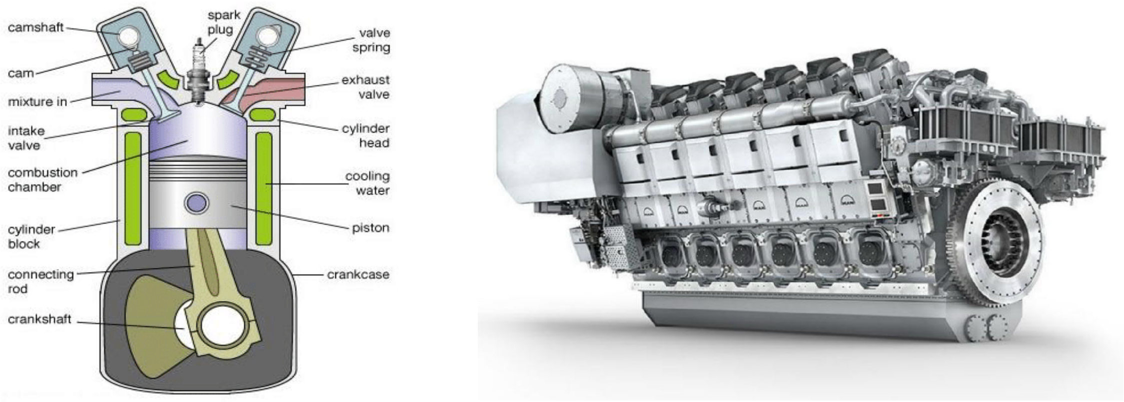
$$P = T \times \omega = T \times 2\pi \frac{rpm}{60} \qquad (8.1)$$

Similarly to all internal combustion engines the diesel engine operates with a fixed sequence of events, which may be achieved either in four strokes or two, a stroke being the travel of the piston between its extreme points. Each stroke is accomplished in half a revolution of the crankshaft. **Diesel engines can be classified on the basis of their rotating speed** (low speed engine <400 rpm; medium speed engine : 400-1200 rpm; high speed engine >1400 rpm) **and their operating principle** (two-stroke; four-stroke). For an overall comparison see Table 8.1 .

Steam turbines have until recently been the first choice for very large power main propulsion units. Their advantages of little or no vibration, low weight, minimal space requirements and low maintenance costs are considerable. A steam turbine can be provided for any power rating likely to be required for marine propulsion. However, the higher specific fuel consumption when compared with a diesel engine offsets these advantages. Refinements such as reheat have narrowed this gap. Steam, after expansion in the high-pressure turbine, is returned to the boiler to be reheated to the original superheattemperature.A steam turbine generates mechanical work from the energy stored in steam.The steam is used to move the pistons at very high pressure (approximately 60 bar at 510^{o}C). The high-pressure steam from the boiler is expanded in nozzles to create a high-velocity jet of steam. The nozzle acts to convert heat energy in the steam into kinetic energy. This jet is directed into blades mounted on the periphery of a wheel or disc (Figure 8.2). The steam does not blow the wheel around. The shaping of the blades causes a change in direction and hence velocity of the steam jet. Steam turbines use various choices of fuel like, diesel, LNG or nuclear. In general their fuel efficiency is low (i.e. in the range of 230g/kW-290g/kW) which depends on the circulation and the power of the engine. This way of producing energy is also very bulky and heavy as it requires more equipment, but it is technologically simple and reliable.

Engine type	Low speed (2 stroke)	Medium speed (4 stroke)	High Speed (4 stroke)
Rotational speed (rpm)	60-250	400-800	>1400
Fuel Efficiency (SFC) (g/kWh)	160-180	170-190	220-240
Power range (MW per cylinder)	0,7-4	0,4-1,3	0,005-0,375
Weight (kg/kW)	20-40	8-20	4-7
Price (USD/kW)	400-500	200-300	200-300
Usage	Common on large cargo ships	Common on passenger ships, RORO ships and icebreakers	Common on fast ships, naval ships, small vessels and used as emergency generators on bigger ships.

Table 8.1 Comparison of diesel engine types



(a) (b)

Figure 8.1 Demonstration of 4 stroke diesel engine

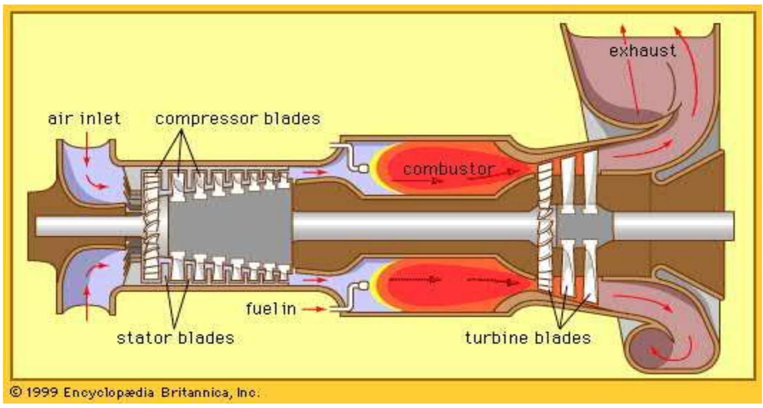


Figure 8.2 Energy conversion process in a steam turbine (Image credit : https://www.britannica.com)

Figure 8.3 Steam turbine plant (Image credit : https://en.wikipedia.org)

In **gas turbines** the air is compressed to a high pressure and energy is added by spraying fuel into the air. This combustion process produces energy which rotates the shaft to drive the compressor. The excess energy is then used to produce thrust or work via an independent turbine that helps rotate the ship's propeller. Gas turbines have relatively low fuel efficiency (approx. 220-260 g/kWh depending on operating conditions) and require the use of high quality Marine Gas Oil. The weight to power ratio is low in the range of 0,8-1,2 kg/kW and 10-30 MW/unit. However, it is light, small in size and generally susceptible to fewer breakdowns. It is environmentally friendly, but the fuel consumption is high; hence economic feasibility is questionable.

Figure 8.4 GE Marine Solutions LM2500 turbine Gas turbine plant (Image credit : https://dieselgasturbine.com)

The power that is produced by the main power generating engine must be transferred to the propeller by a transmission system. There are various methods to do this namely, mechanical system, electric system, and hydraulic system. **Mechanical transmition systems** have a direct transmission where the rotated shaft is directly running the propeller or the power produced is transmitted through a gearbox where the gear ratios are used to change the speed of the propeller without changing the speed of the engine. In **electrical transmission** the engine runs a generator which is then transferred through a switchboard to ta motor running the propellers. This is used in passenger and cruise ships because there are demands for electricity for the hotel operations and a varying ships speed is seen. Icebreakers require high torque which makes an electric motor the ideal transmission unit. It is also used in ships that require a lot of electric energy due to the equipment onboard. **Hydraulic transmission** systems are similar to mechanical systems with a gearbox where the gearbox is replaced with the hydraulic vane pump. The pump draws hydraulic fluid from the storage tank and delivers it to the direction control valve at high pressure. This control valve determines the direction and volume of fluid needed for the rotation of the hydraulic motor which in turn drives the propeller.

3. Introduction to ship resistance

A ship must be designed to propel through water with maximum efficiency ideally via use of minimum power. Hence, the magnitude of resistance on the ship's hull, RT, is naturally paramount for the power required to move the ship If the naked hull of the vessel is driven through water by a device which does not interfere with the hull, then we get the **total resistance R_T**. **Ship effective power** is defined as the power required to overcome this resistance at the given speed of the vessel. It is defined as:

$$P_E = R_T \times V \qquad (8.1)$$

R_T. comprises of **frictional (R_F), residual (R_R) and air resistance (R_A)** components. Thus,

$$R_T = R_F + R_R + R_A \qquad (8.2)$$

The influence of frictional resistance depends on the thin water viscosity boundary layer generated around the hull surface as the ship progresses in waves. The magnitude of residual resistance describes the energy lost by the ship setting up waves, eddies and by the viscous pressure resistance, which all depend on the hull lines. For slow moving ships such as tankers and bulkers, the frictional resistance is often of the greatest influence (70-90%) whereas for fast going ships, such as panamax container carriers, the frictional resistance may account for as little as half of the combined resistance. It is not possible to make a perfectly streamlined design above the water form as there are difficulties of fabrication and these difficulties are not justified by the amount of resistance reduced. Thus eddies are formed due to the discontinuities in a ship's superstructure and because the streamlines are broken. Air resistance normally represents about 2% of the total resistance, however, with a significant increase up to approx. 10% for ships with large superstructures such as container ships with containers stacked on deck. If wind resistance is considered, the figures may increase. There are various methods to measure hull resistance (e.g. Holtrop & Mennen, Taylor & Getler etc.). However, each of these methods have a limited range and are valid only for certain speeds and hull forms. Ice resistance in areas where the sea freezes over and is dominant for icebreakers.

Practical Exercise. Calculate the total resistance of a ship with principal particulars outlined on Table 8.2 at a design speed of 25 knots (12.86 m/s). Other characteristics of the vessel have been assumed or calculated for you in Table 8.3 to simplify the problem.

Item	Value	Unit
L_{PP}	205	m
B	32	m
T	10	m
LCB	2.02 (aft Amidships)	%
C_P	0,583	-
C_B	0.572	-
∇	37500	m^3
C_M	0.980	-
C_{WP}	0.570	-
A_{BT}	20	m^2
C_{stern}	10	-
T_f	10	m
T_a	10	m
h_B	4	m
A_t	16	m^2
S	7205.004	m^2
S_{APP}	50	m^2

Table 8.2 Ship Principal particulars

Item	Value	Unit
$(1+k_1)$	1.156	-
$(1+k_2)_{eq}$	1.5	-
c_1	1.398	-
c_2	0.7595	-
c_5	0.9592	-
m_1	-2.1274	-
m_2	-0.17087	-
λ	0.6513	-
d	-0.9	-
w	0.2584	-
t	0.1747	-

Table 8.3 Additional wave resistance factors according to Holtrop and Mannen

Solution.

Hull viscous resistance is the component of water resistance due to viscosity; the water particles exert frictional drag on the ship's hull. It comprises the frictional drag due to the surface of the hull and another sub-component due to the local flow field as a result of the ship's form and this is known by the form effect. This component can be solved using the following equations:

$$R_v = 0.5(1+k_1)\rho S V^2 C_F, \quad C_F = \frac{0.075}{(\log(\mathrm{Re})-2)^2}$$

Where C_F is the frictional coefficient according to the IITC 1957 line formula which is a function of the Reynold's number $\mathrm{Re} = \frac{VL}{\upsilon}$. $(1+k_1)$ is the form factor multiplied by the frictional drag gives the viscous resistance:

$$\mathrm{Re} = \frac{12.86 \times 205}{1.1897 \times 10^{-6}} = 2215805332$$

$$C_F = \frac{0.075}{(\log(2215805332)-2)^2} = 0.001390$$

$$R_v = 0.5 \times 1.156 \times 1025 \times 7381.45 \times (12.86)^2 \times 0.00139 = 1005.29 \text{ KN}$$

Appendage resistance is the viscous resistance of the appendages attached or fitted to the hull. Appendages include any part that stick out of the bare hull below the waterline (e.g. rudders, thrusters, bilge keel, etc.). It has the same equation as the hull viscous resistance (with separate combined form factor for all the appendages).

$$R_{App} = 0.5\rho S_{App} V^2 (1+k_2)_{eq} C_F = 0.5 \times 1025 \times 50 \times (12.86)^2 \times 1.5 \times 0.00139 = 8.83 \text{ KN}$$

The ship when moving in water generates a typical wave system which contribute in the total resistance and known by wave-making resistance. You can imagine it as the energy absorbed in forming such waves. It is given by the following equation:

$$R_W = c_1 c_2 c_5 \nabla \rho g \;\exp(m_1 Fn^d + m_2 \cos(\lambda Fn^{-2}))$$

$$c_1 = fn(L, B, T, i_E),\; c_2 = fn(A_{BT}, B, T, T_F, h_B),\text{ and } c_5 = fn(A_T, B, T, C_M)$$

$$m_1 = fn(L, T, \nabla, B, C_P),\; m_2 = fn(L/\nabla^{1/3}, C_P, Fn),\; \lambda = fn(L/B, C_P),\text{ and } d = -0.9$$

To simplify the problem these coefficients have been calculated for you in table (2).

$$\begin{aligned} R_W &= 1.398 \times 0.7595 \times 0.9592 \times 37500 \times 1025 \times 9.81 \times \exp((-2.1274 \times 0.2868^{-0.9}) \\ &+(-0.17087 \times \cos(0.6513 \times 0.2868^{-2}))) = 557.1 \text{ KN} \end{aligned}$$

The bulbous bow resistance is an additional part of the hull at the bow that contributes in reducing wave making resistance by initiating waves that cancel out the waves produced by the hull's pressure points. However, bulbous bow is considered as an additional wetted surface which increase the frictional drag. The additional resistance due to the presence of the bulbous bow is given by:

$$R_B = 0.11\exp(-3P_B^{-2}) Fn_i^3 A_{BT}^{1.5} \rho g / (1+Fn_i^2)$$

Where P_B is a coefficient measures the immersion of the bow and Fn_i is the Froude number based on immersion and are given by:

$$P_B = 0.56\sqrt{A_{BT}} / (T_F - 1.5h_B)$$

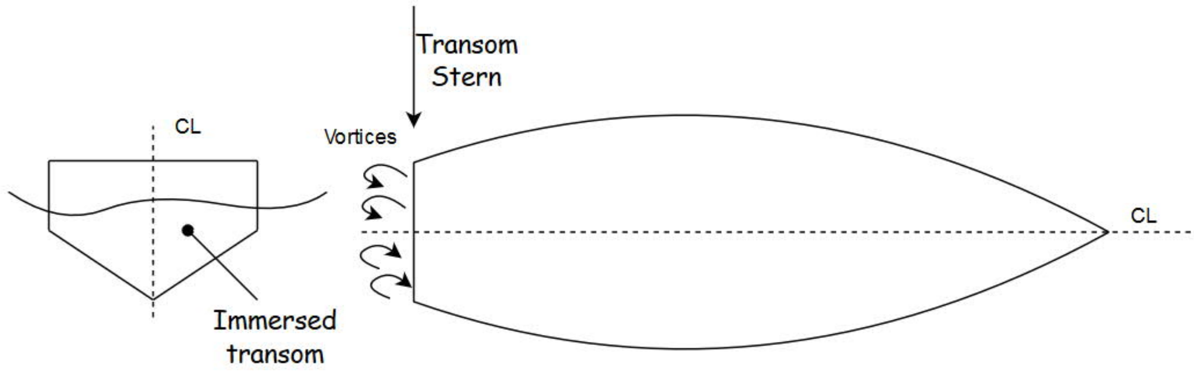
$$Fn_i = V / \sqrt{g(T_F - h_B - 0.25\sqrt{A_{BT}}) + 0.15V^2}$$

$$\therefore P_B = 0.56 \times \sqrt{20} / (10 - (1.5 \times 4)) = 0.6261$$

$$Fn_i = 12.86 / \sqrt{9.81(10 - 4 - 0.25 \times \sqrt{20} + 0.15 \times (12.86)^2} = 1.5084$$

$$R_B = 0.11\exp(-3 \times 0.6261^{-2}) \times 1.5084^3 \times 20^{1.5} \times 1025 \times 9.81 / (1 + 1.5084^2) = 0.0491 \text{ KN}$$

Ships are often designed with transom stern for reduced length and wider deck aft. The flow around the transom stern differs from the cruiser(rounded) stern. Transom stern immersion induces some eddies downstream and consequently increases the pressure resistance known as <u>*transom stern resistance*</u>.



Transom immersion resistance is obtained using the following equations:

$$R_{TR} = 0.5\rho V^2 A_T c_6$$

$$c_6 = 0.2(1 - 0.2Fn_T) \quad \text{for } Fn_T < 5$$
$$c_6 = 0 \quad \text{for } Fn_T \geq 5$$

$$Fn_T = V / \sqrt{2gA_T / (B + BC_{WP}} = 12.86 / \sqrt{2 \times 9.81 \times 16 / (32 + 32 \times 0.57)} = 5.144$$
$$\therefore c_6 = 0$$

$$\therefore R_{TR} = 0$$

Mainly, these equations depend on model tests in towing tanks. There must be a correction for the model test resistance values when correlate to the full-scale. The reason behind that is the additional resistance on the full-scale due to the difference in the surface roughness between the model and the ship, and the difference in the still-air resistance. This resistance is termed as <u>*model testing induced resistance*</u> and is given by:

$$R_A = 0.5\rho SV^2 C_A$$

$$C_A = 0.006(L + 100)^{-0.16} - 0.00205 + 0.003\sqrt{L / 7.5}C_B^4 c_2 (0.04 - c_4)$$

$$c_4 = T_F / L \quad \text{for } T_F / L \le 0.04$$
$$c_4 = 0.04 \quad \text{for } T_F / L > 0.04$$

$$T_F / L = 0.0488, \quad \therefore c_4 = 0.04$$

$$\therefore C_A = 3.525 \times 10^{-4}$$

$$R_A = 0.5 \times 1025 \times 7381.45 \times (12.86)^2 \times 3.525 \times 10^{-4} = 221 \text{ KN}$$

The *total resistance* is the summation of the previous components:

$$R_T = 1005.29 + 8.83 + 557.1 + 0.0491 + 221 = 1793 \text{ KN}$$

4. Ship propulsion

The force required to propel the ship is obtained by causing a stream of water (and possibly air) creating a thrust in the opposite direction to that of the ship motions. We can use wind power (e.g. fletner rotors, sails) to propel the ship forward (Figure 8.5).

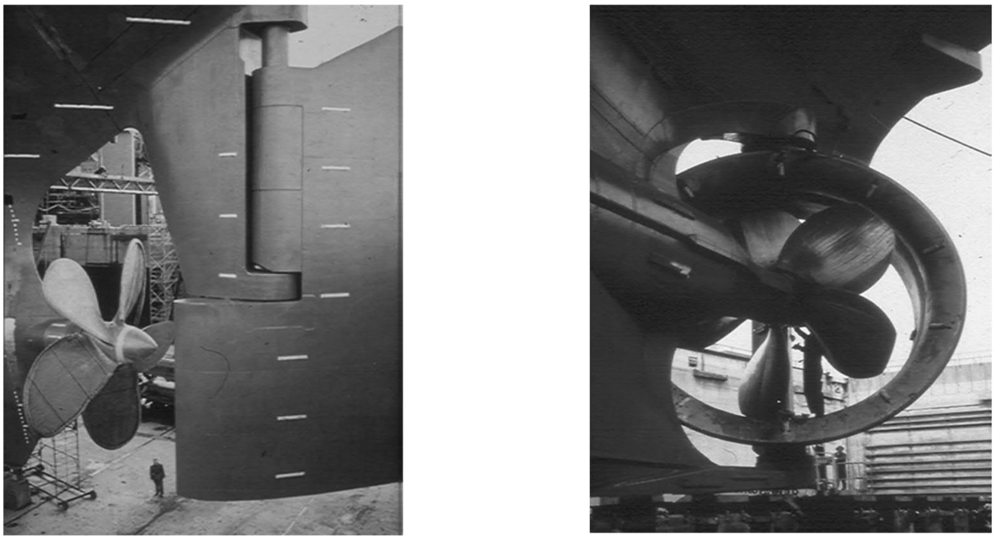
(a)Image Credit: https://www.maritime-executive.com (b) Image credit : https://safety4sea.com

Figure 8.5 Wind assisted propulsion solutions

Marine propellers are made from corrosion-resistant materials (e.g. alloy of aluminum and stainless steel). Other popular materials used are alloys of nickel, aluminium and bronze which are 10~15 % lighter than other materials and have higher strength. Propellers are be classified on the basis of **number of blades** or by **blade pitch** (see Tables 8.1,8.2). **Screw propellers** are the most common type of propulsion device used. They consist of helicoidal surfaces (blades) that rotate through the water (Figure 8.6). This rotational motion creates a pressure difference between the forward and rear surfaces of the propeller blades which produces thrust pushing the ship forward. They can turn clockwise or anti-clockwise. In modern passenger ships and LNG carriers we find a twin propeller specification; i.e. 2 propellers are used to produce the thrust. Most marine screw propellers have fixed blades and produce only a certain thrust and torque at a certain rpm. Controllable/variable pitch propellers have blade adjustment capability; i.e. they can produce varied thrust / torque at the same rpm by adjusting the pressure difference between the blades.

Propeller type	Technical Characteristics	Advantages	Limitations
Fixed Pitch	• Blades permanently attached (casted) to the hub	Reliable as the system doesn't incorporate any mechanical and hydraulic connections	Fitted in ships of limited maneuverability demands
Variable pitch	Blade rotation and pitch variation possible	Good maneuverability and engine efficiency	High risk for oil pollution as hydraulic oil in the boss mechanism used for controlling the pitch may leak out

Table 8.1 Propeller classification based on pitch



(a) Large 4 bladed propeller of a bulk carrier

(b) Steerable ducted propeller

Figure 8.6 Some ship propellers (Image Credit: https://www.marineinsight.com/)

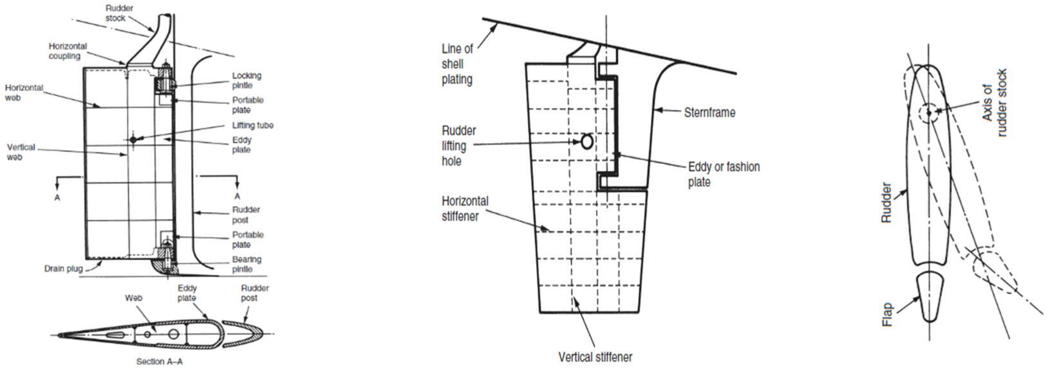
Propeller type	Technical Characteristics Characteristics
3 blade propeller	• The manufacturing cost is low • Material: aluminium alloy • Gives a good high-speed performance • The acceleration is better than other types • Low-speed handling is not much efficient.
4 blade propeller	• The manufacturing cost is higher than 3 blade propellers • Material: stainless steel alloys • Good strength and durability • Good low-speed handling and performance • Good holding power in rough seas • Good fuel economy
5,6 blade propellers	• Manufacturing cost is higher • Vibration is minimal • Excellent holding power in rough seas • Low pressure field over the propeller decreases

Table 8.2 Propeller classification based on number of blades

Azimuth thrusters or pods are propulsive devices with full rotational capability (360^{o}) and enable excellent ship manoeuvrability. **Mechanical transmission thrusters**, connect a motor inside the ship to the outboard unit by gearing. The motor may be diesel or diesel-electric. Depending on the shaft arrangement, mechanical azimuth thrusters are divided into L-drive and Z-drive. An L-drive thruster has a vertical input shaft and a horizontal output shaft with one right-angle gear. A Z-drive thruster has a horizontal input shaft, a vertical shaft in the rotating column and a horizontal output shaft, with two right-angle gears.In **electrical transmission pods**, an electric motor is fitted in the pod itself, connected directly to the propeller without gears. The electricity is produced by an onboard engine, usually diesel or gas turbine. ABB Group's Azipod was the first product using this technology Figure 8.7). They have good hydrodynamic performance, low vibrations, and ergonomics as they have an inbuilt transmission system which is usually electric. However, their cost is high and their efficiency low as compared to traditional mechanical transmission systems. They are commonly used on passenger ships, ice going ships and supply ships as these require high manoeuvrability.

Figure 8.7 ABB Azipod thruster (Image Credit: ABB)

Rudders are devices used for steering and manoeuvring a vessel. They are hydrofoils pivoting on a vertical axis located normally at the stern behind propeller(s) to produce a transverse force and steering moment about the ship centre of gravity by deflecting the water flow to the direction of the foil plane. Some key rudder types are shown on Figure 8.8.

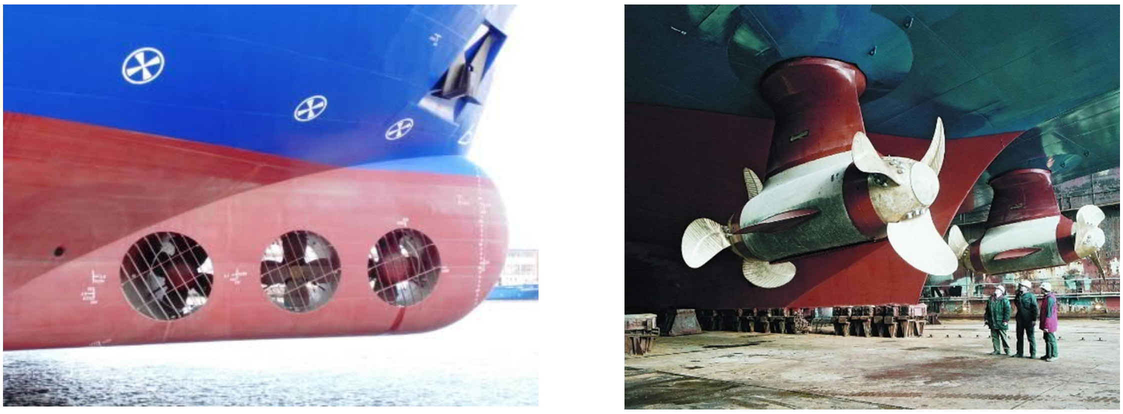


(a) balanced rudder (b) semi-balance rudder (c) flap rudder

Figure 8.8 Typical ship rudders (Tupper, 2013)

Rudder effectiveness can be improved by improving the rudder arrangement in the propeller stream, increasing the rudder area, selecting a better rudder type (e.g. spade rudder instead of semi-balanced rudder, high lift profiles or flap rudders), using a steering gear which allows larger rudder angles than the customary 35 deg. or by implementing shorter rudder steering time by introducing a more powerful hydraulic pump in the steering gear. Rudders are one of the areas where extra investment spent on getting the right equipment can pay back. One of the basic problems is deciding whether to optimise the rudder for the service speed or for low-speed manoeuvring. Many rudder configurations can meet guidelines for turning circles and zig zag manoeuvres, but still they are not optimum for the ship service profile. For ships like VLCCs and container vessels, the majority of service is course keeping. Consequently, rudder angles during normal course keeping and manoeuvring operation are limited to 35 deg. For some service profiles good slow speed performance is very important and high rudder operating angles will give greater benefit.

Thrusters in way of a ship’s bow or stern are transversal propulsion devices built into, or mounted to either the bow or stern of a ship or a boat to make her more manoeuvrable. Practically they are used to allow ships to be more independent from tugs, give them more maneuverability at low speeds (e.g. when maneuvering in ports). There are three general types of thruster devices namely : (a) the lateral or **tunnel thruster**, which consists of a propeller installed in a athwartship tunnel; (b) the **jet thruster** which consists of a pump taking suction from the keel and discharge to either side and (c) the **azimuthal thruster**, which can be rotated through 360°. Bow thrusters make docking easier, since they allow the captain to turn the vessel to port or starboard side, without using the main propulsion mechanism which requires some forward motion for turning. Modern large ships (e.g. passenger might have multiple bow thrusters and stern thrusters. Large vessels usually have one or more tunnel thrusters built into the bow, below the waterline. An impeller in the tunnel can create thrust in either direction which makes the ship turn. Most tunnel thrusters are driven by electric motors, but some are hydraulically powered. These bow thrusters, also known as tunnel thrusters, may allow the ship to dock without the assistance of tugboats, saving the costs of such service. During vessel design, it is important to determine whether tunnel emergence above the water surface is commonplace in heavy seas. Tunnel emergence hurts thruster performance, and may damage the thruster and the hull around it. The general arrangement and hull form of new buildings incorporating thrusters can be modified significantly in order to increase hydrodynamic efficiency. A key advantage is that they tend to suffer less from vibration and noise and are therefore well suited for use on passenger vessels. Since thrusters are steerable, using them may also eliminate the ship rudder.



(a) bow thrusters

(b) azimouth thrusters

Figure 8.9 Examples of ship thrusters (a) bow thrusters (b) azimuth thrusters

5. Powering calculations

The propulsion system interacts with the ship's hull in forming the flow around them. The flow induced to the propeller is changed due to the hull form. On the other hand, the flow around the hull is affected by the propeller existence behind it. The traditional way of dealing with this complex hydrodynamic problem is to consider them separately in analysis, design, and testing, then to introduce some efficiencies to account for this interaction. The general form of calculating the power is *force × speed*.

If we consider only the hull towed in a tank by some external force, thus, the power required to move the ship at the design speed mentioned above is known by the effective power:

$$P_E = R_{total} \times V = 1793 \times 12.86 = 23058 \text{ KW}$$

Let us consider now the propeller operating in open water without the hull. The power produced by the propeller is the thrust power:

$$P_T = T \times V$$

However, this is not real, as the flow speed directly upstream the propeller differs from the ship speed due to the ship's wake, and the speed directly upstream the propeller(on the suction side) is called the speed of advance V_A and the thrust power is: $P_T = T \times V_A$.

The relation between the ship speed and the speed of advance is connected with a term called the wake fraction, and it indicates how much the wake is affecting the flow velocity directly before the propeller:

$$w = 1 - \frac{V_A}{V}$$

$$V_A = (1 - 0.2584) \times 12.86 = 9.537 \; m/s$$

It can be calculated numerically or by using empirical formulae in preliminary design approaches.

The empirical formula we used to obtain the wake fraction (table 2) is a function of some parameters as shown:

$$w = fn(C_V, L, B, C_P, D, T_A, C_B, C_{stern})$$

On the other hand, the thrust measured when the propeller is behind the hull is higher than the total resistance without the propeller. So, the propeller induces some additional resistance due to some reasons (the propeller increases the flow velocities in the aftbody which increases friction and reduces pressure behind the hull which increases the pressure resistance). The term that connects the relation between the total resistance and the thrust is known by the thrust deduction factor:

$$t = 1 - \frac{R_T}{T}$$

An empirical formula used to obtain the thrust deduction factor: $t = fn(LCB, C_P, L, B, D, C_{stern})$.

The difference between the effective power and the thrust power combines together the wake effects and the thrust deduction effects. The ratio between them is called the hull efficiency:

$$\eta_H = \frac{P_E}{P_T} = \frac{R_T \cdot V}{T \cdot V_A} = \frac{1-t}{1-w} = \frac{1-0.1747}{1-0.2584} = 1.11$$

Noted that this efficiency can be more than unity, that's because those two factors- previously mentioned, can have some beneficial effects on the power.

The power delivered from the shaft to the propeller is expressed by the torque and rpm:

$$P_D = 2\pi \cdot n \cdot Q$$

The losses between the delivered power and the thrust power is expressed in terms of the behind hull efficiency $\eta_B = P_T / P_D$. This ratio is different when the propeller is considered alone without the hull which is known by the open water efficiency (η_o). The factor that accounts for the differences between the case where the propeller is behind the hull and the open water condition is known by the relative rotative efficiency:

$$\frac{P_T}{P_D} = \eta_o \times \eta_{RR}$$

The regression formula gives the relative rotative efficiency as a function of the blade area ratio of the propeller A_E / A_o which is a propeller characteristic:

$$\eta_{RR} = fn(A_E / A_o, C_P, LCB) = 0.9931$$

The delivered power P_D is less than the brake power of the engine due to losses in shafts and bearings. So, the ratio between the delivered power and the brake power represents the shaft efficiency which can be assumed as 98%.

$$\eta_s = \frac{P_D}{P_B} = 98 - 98.5\%$$

The brake power is what you need for your design and it is the main aim of this analysis. Using the brake power, you can select the prime movers of your ship project.

$$P_B = \frac{P_E}{\eta_H \eta_o \eta_{RR} \eta_s} = \frac{R_T \cdot V}{\eta_H \eta_o \eta_{RR} \eta_s}$$

The final step to calculate the brake power is to obtain the open water efficiency. Usually this needs open water tests. There are some equations used to estimate the open water efficiency and the other propeller characteristics by polynomial representation of the test results. Propeller design is an iterative process and you shall first estimate some main characteristics such as the diameter or the rpm, then calculate the torque coefficient, the thrust coefficient, and the open water efficiency, and finally to compare the thrust produced to the thrust required for your hull. If the thrust produced is lower than the required, you shall start another calculation process. You can find more details in propeller design using methodical series in [2]. For this example, propeller main characteristics are given as follows:

Item	Value	Unit
Number of Blades ***Z***	5	-
Propeller diameter ***D***	8	m
open water efficiency $\boldsymbol{\eta_o}$	0.6461	-

Eventually, the brake power $P_B = \frac{P_E}{\eta_H \eta_o \eta_{RR} \eta_s} = \frac{23058}{1.11 \times 0.6461 \times 0.9931 \times 0.98} = 33035.42$ KW

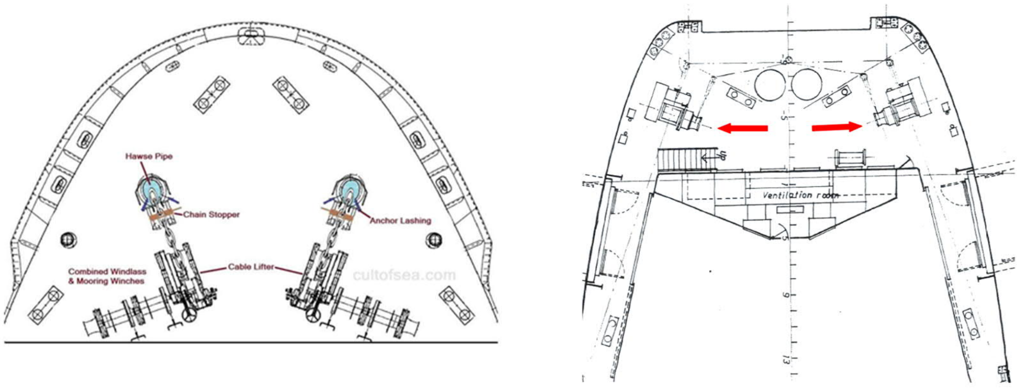
Noted that we assume there is no losses between the shaft and the engine, so the shaft power is equal to the brake power.

6. Ship Equipment and components – brief reference

Ship anchoring and mooring are important activities of a marine platform at the port or in shallow waters. The crew of the ship normally do the needful in this respect using ship's mooring ropes, anchor chains, associated machinery such as anchor windlasses, mooring winches, capstans and mooring fittings on deck such as bitts or bollards and fairleads and chocks of various kinds. Normally, on a ship these deck machinery and fittings are provided in way of the bow on the forecastle deck and in the aft on the poop deck (see Figure 8.10). It is a regulatory requirement that the space in these areas is enough not only to house the machinery and equipment, but also provide enough space for ropes and chain to pass conveniently for enough working space.

There are two basic anchor types namely **stockless** and **stock** A ship anchoring system is control from the bridge and consists of the anchor, anchor chain and anchor handling equipment. The overall purpose of the system is to maintain a ship's position so that she does not drift off due to wind/currents and/or waves. To ensure high operational reliability all ships have 2 bow anchors. When launched together they help reduce ship yaw via equal weight distribution. Inland water way ships also have a stern anchor. The force on an anchor is horizontal acting along the bottom of the seabed otherwise (e.g. if the force is vertical) ship heaving and uprooting of the anchor from the seabed may occur (see Figure 8.11). The weight of the anchor is measured in tons and is decided based on the ship size. The holding capacity of an anchor is measured by the anchors holding power which is the force exerted on the anchor by the ship. The chain is also an integral part of this system. It must be long enough to support the force of the ship and this affects the holding capacity of the anchor. The chain should also act on the anchor horizontally and must dampen the stopping forces. The handling system consists of various parts namely the chain locker, the brakes for the capstan, guiding and controlling mechanisms.

In a merchant vessel, if cargo handling gear is provided on the upper deck space must be provided for housing and working of the cargo machinery such as cranes and derricks and also space for hatch cover panels when open. Arrangements should be such that the hatches can be opened and closed conveniently as per the recommendations of the supplier so that cargo movement (loading and unloading) can be done efficiently. Access of crew members from accommodation to work space on deck must be available in all weather conditions.



1. typical forecastle deck arrangement
2. typical poop (aft) deck arrangement

Fig 8.10 Typical mooring arrangements (Image credit : https://cultofsea.com/)

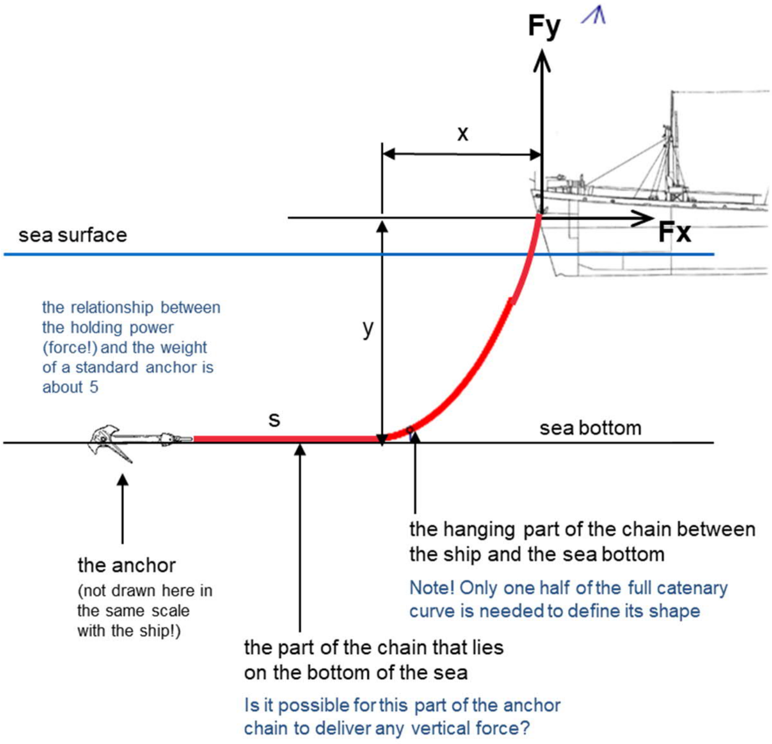
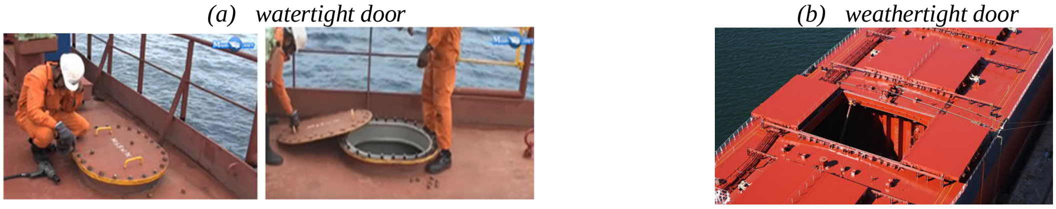


Fig 8.11 Basic dynamics of ship anchorage system (Image credit : https://cultofsea.com/)

(a) watertight door *(b) weathertight door*



(c) manhole

(d) Roll on / off hatch cover of a bulk carrier (image credit https://www.macgregor.com)

(e)

Fig 8.12 Ship doors and hatches (Image credit : https://cultofsea.com/)

Mooring systems are auxiliary to anchoring and are used to guide a ship to her correct quay location and to hold her fixed in the lateral and in longitudinal directions. They are designed such that the forces acting on the ship by waves, winds and currents are counterbalanced. Thus changes in a ship's draught, heel and trim needs to be accounted for while designing the system. The components of a mooring system are called **mooring lines**. **Breast lines** are perpendicular to the quay and may be added to counteract high environmental forces such as winds and waves. **Spring lines** prevent a moored ship from moving along the quay and provide longitudinal fixing. Most of the mooring lines are made from synthetic materials like nylon, polyester and polypropylene. They are stored on reels and can be used to tow the ship too if separate towing lines are not present. The line is handled with capstans or winches and the direction of the pull force is adjusted with rollers and chokes. The track of the line should always be minimized, and the total number of lines is adjusted so that least number of lines are needed to keep the ship in place. It is regulatory requirement to keep all lines in direct sight of the operator.

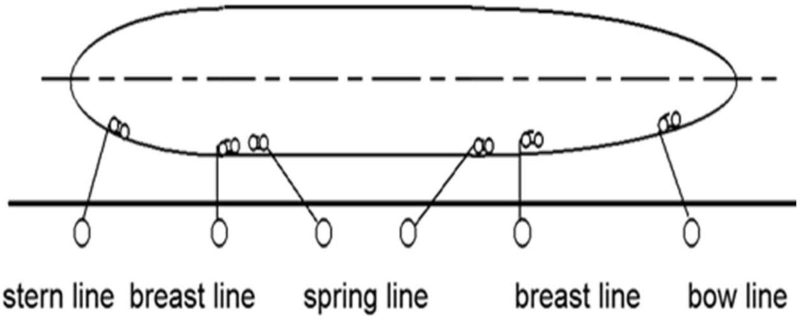


Figure 8.13 Mooring of a ship to a dock (Image Credit: shoretension)

Ship evacuation systems are very important part of safe operations/design and they are regulated in accordance with IMO SOLAS requirements. Evacuation system components include escape routes, muster stations, lifeboats/rafts and their launching mechanisms, life vests and last but not least evacuation procedures. To date, most fatal accidents during evacuation have been caused due to failures in lifeboat release mechanisms. The rescue of the evacuation personnel must be planned too and communication to the maritime emergency services must be done.There are various requirements for lifesaving appliances.

(a) mustering onboard *(b) Costa Concordia.* *(c)Life raft at sea*

3. *evacuation slide* 4. *ship life rafts* 5. *launching of a life boat*

Figure 8.14 Demonstration of ship life saving equipment (Image Credit: shoretension).

7. Questions

1. Name the components of a ship propulsion system and give examples of those.
2. What are the main parts of diesel-electric propulsion system?
3. Define the main engine for 15,000 TEU container ship. Justify you selection.
4. Name the most important differences between a slow speed diesel engine and a medium speed diesel engine. Give examples of the advantages and disadvantages in each case.
5. List 3 of the most potential energy sources for a passenger ship. Discuss them from viewpoint of SWOT analysis (strength, weakness, opportunity and threat).
6. Explain what we mean by ship operational profile and how it influences power plant design.
7. What are the benefits of Azipod-system in large passenger ships?
8. Explain the benefits and weaknesses of podded propulsion systems.
9. Name the most important lifesaving appliances in ships.
10. Shallow-draft vessels have often rudders with a long profile but a low height. Characterize their use and the distinctions when compared to a rudder of a ship with bigger draught, a rudder with a shorter profile and greater height.
11. Describe the forces and principles acting on the ship when anchored.